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Development, Design, and Operation of a Cascade Impactor to Collect Aerosol Samples for Wavelength Dispersive X-Ray Fluorescence Analysis

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DEVELOPMENT, DESIGN, AND OPERATION OF A CASCADE IMPACTOR TO COLLECT AEROSOL SAMPLES FOR WAVELENGTH DISPERSIVE X-RAY FLUORESCENCE ANALYSIS

by

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16. ABSTRACT

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A five-stage slit impactor was designed to accomplish this goal. The impactor uses an oscillating drum beneath each jet to collect the sample evenly over a 31 mm x 34 mm area. The impactor is constructed from 316 stainless steel and will fit through a 4-inch sampling port. A right-angle pre-impactor is used at the inlet to reduce inlet losses and provide a 15 micrometer aerodynamic cut.

Special substrates and substrate coatings were found which offer good particle retention at sampling temperatures and provide low x-ray background.

Calibration studies were conducted with a prototype unit designed to allow various slit widths and jet to plate spacings. These studies provided the design criteria used for dimensioning the final impactor.

With this sampling system samples can be readily collected which can be directly analyzed by wavelength dispersive x-ray fluorescence analysis for elemental composition. No sample preparation will be required other than mounting the substrate in a carrier for the analysis.

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ABSTRACT

The goal of this research project was to design and construct a particle sizing device that will collect and size source emitted aerosols on 47 mm diameter substrates for subsequent wavelength dispersive x-ray fluorescence analysis.

A five stage slit impactor was designed to accomplish this goal. The impactor uses an oscillating drum beneath each jet to collect the sample evenly over a 31 mm x 34 mm area. The impactor is constructed from 316 stainless steel and will fit through a 4 inch sampling port. A right-angle pre-impactor is used at the inlet to reduce inlet losses and provide a 15 micrometer aerodynamic cut.

A complete sampling system was designed for the impactor. This system includes a 10 foot probe and I-beam support, a modified Andersen EPA Control Unit for flow and flow measurement, and a Central Control Unit which governs all sampling.

Calibration studies were conducted with a prototype unit designed to allow various slit widths and jet to plate spacings. These studies provided the design criteria used for dimensioning the final impactor.

Special substrates and substrate coatings were found which offer good particle retention at sampling temperatures and provide low x-ray background.

With this sampling system samples can be readily collected which can be directly analyzed by wavelength dispersive x-ray fluorescence analysis for elemental composition. No sample preparation will be required other than mounting the substrate in a carrier for the analysis.

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SECTION I

INTRODUCTION

A novel cascade impactor for in situ flue gas sampling has been developed. This device differs from all other in-stack impactor designs because it is intended to collect size segregated particles in such a manner that no sample preparation is necessary in order to perform X-ray fluorescence (XRF) elemental analysis on each stage catch.[1] The work described here was solely concerned with the development of a sampler that is capable of providing samples in a form that are directly compatible with the requirements of XRF analysis and not with the analytical technique itself. Several system parameters were set specifically to provide samples in the form required by an automated wavelength dispersive XRF system operated by the U.S. EPA at Research Triangle Park, North Carolina. The optimum sample configuration for this spectrometer is a thin, non-metallic, 47 mm disk. The sampler requirements, as specified by the EPA, are given in Table 1. Potential uses for the device include data collection for use in source-receptor studies, particularly, studies to be carried out in conjunction with the Inhalable Particulate (IP) program.

The 47 mm diameter collection substrates are coated with high melting, low WDXRF background polymer. This polymeric coating softens at stack temperatures and acts as a near-ideal impaction surface. The impactor is designed to fit through a standard 4 inch sampling port. Requiring a fit through a 4 inch port precludes the use of a cyclone precutter to obtain an inhalable particulate (IP) cut. Since laboratory and field data have demonstrated that large sampling errors can be induced with bent or buttonhook nozzles,[2,3] a right angle impactor precutter of Southern Research Institute design is used at the inlet to the impactor. The precutter eliminates sampling errors due to bent nozzles and provides the IP 15 micrometer aerodynamic cut at the design flowrate (22.65 ℓpm) and temperature (150°C). Four sampling nozzles are provided--3/8 inch, 1/4 inch, 3/16 inch and 1/8 inch.

Figure 1 shows the disassembled impactor with the precutter attached. From this figure one can see that in concept, this impactor is very similar to the impactor developed by Lundgren[4] for ambient air sampling. This design has five stages and an integral 47 mm back up filter. Each stage of the impactor is a drum. Substrates 47 mm in diameter are mounted on each drum and held in place with spring clips spot welded to the drums. During sampling these drums oscillate synchronously back and forth beneath the slits at a frequency of about 60 Hz. This results in size segregated particulate samples that are uniformly deposited onto each substrate

Table 1. Design Specifications of the Impactor

Number of stages:	5
Stage D_{50}'s, micrometers	8, 4, 2, 1, & 0.5
Operating temperature, °C	to 150
Substrate diameter, mm	47
Diameter of uniform deposition, mm	30
Maximum surface loading, $\mu g/cm^2$	200
Minimum usable port dia., in.	4
Collection substrate	non-fibrous
Capable of isokinetic sampling	
Provide IP particle cutoff	

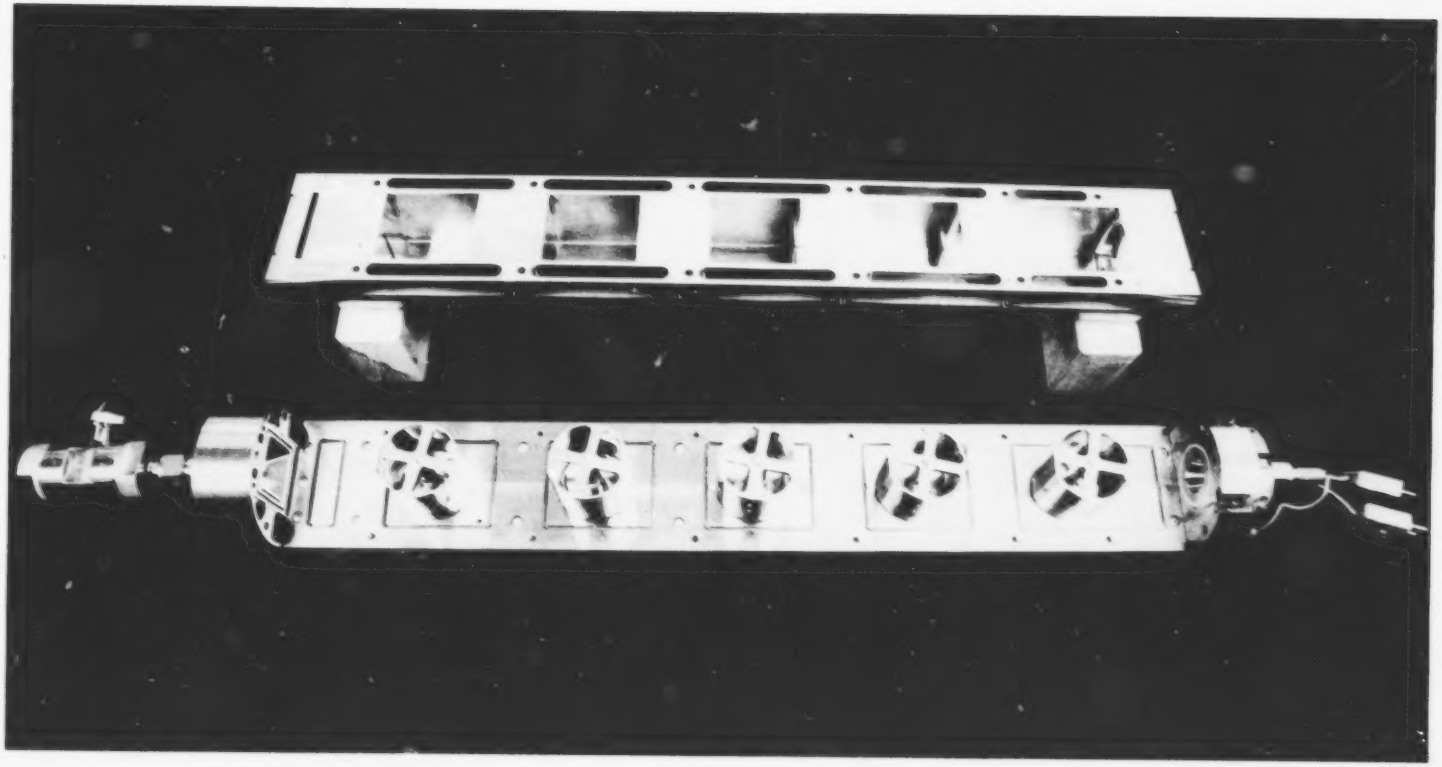

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Figure 1. The disassembled impactor with right angle impactor precutter attached.

on a 31 mm x 34 mm area. During automated wave dispersive XRF analysis an area 30 mm in diameter in the center of each substrate is analyzed. Therefore, the edges of the sample, where some non-uniformity of deposition will occur, are avoided in the analysis. Nominal aerodynamic stage D_{50} values are 8, 4, 2, 1, and 0.5 micrometers at the design flowrate and temperature. The impactor is made out of 316 stainless steel.

Figure 2 shows the assembled impactor attached to specially designed 10 foot sampling probe and I-beam support. The drums are oscillated by means of high speed, high torque stepping motor located on the outboard end of the probe. A drive shaft mounted on sealed bearings couples the motor to the impactor. Figure 3 shows the rear of the probe with the drive stepping motor and motor position indicator. Figure 4 shows a modified Andersen "EPA" control unit which provides flow and flow measurement, and Figure 5 shows the central control unit. The items shown in Figures 1 through 5, plus a punch designed to cut substrates constitute the equipment resulting from this development.

In the rest of this report we will summarize the laboratory calibration and substrate development phases of this project and then describe the in-stack impactor in detail and give instructions for its use.

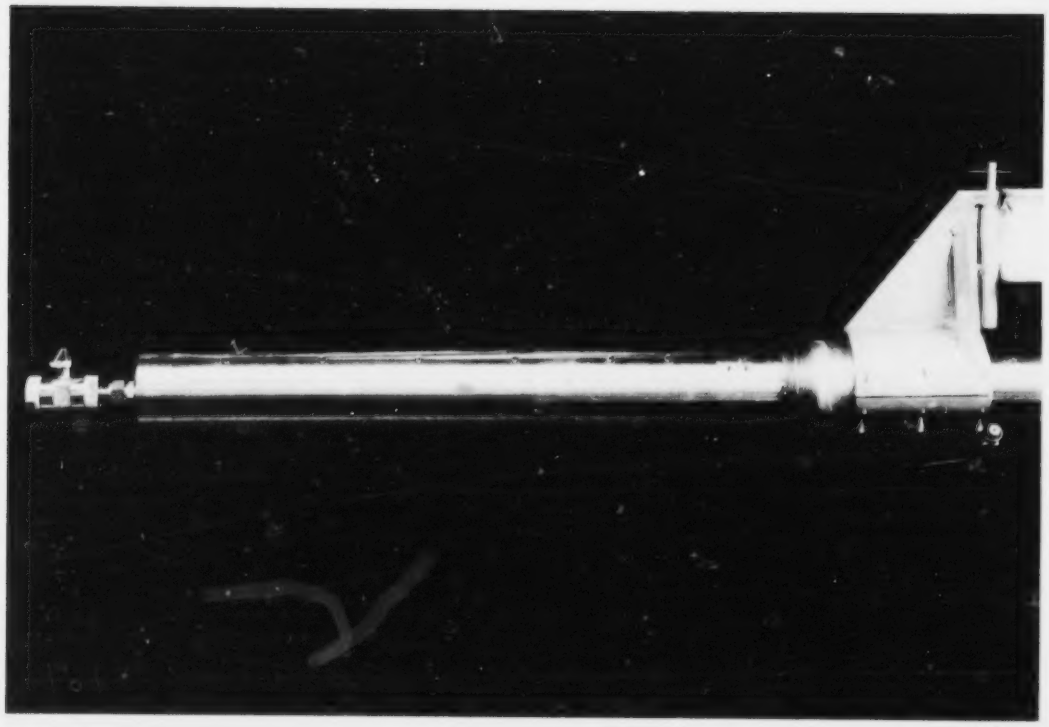

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Figure 2. The impactor attached to the 10-foot sampling probe and I-beam support.

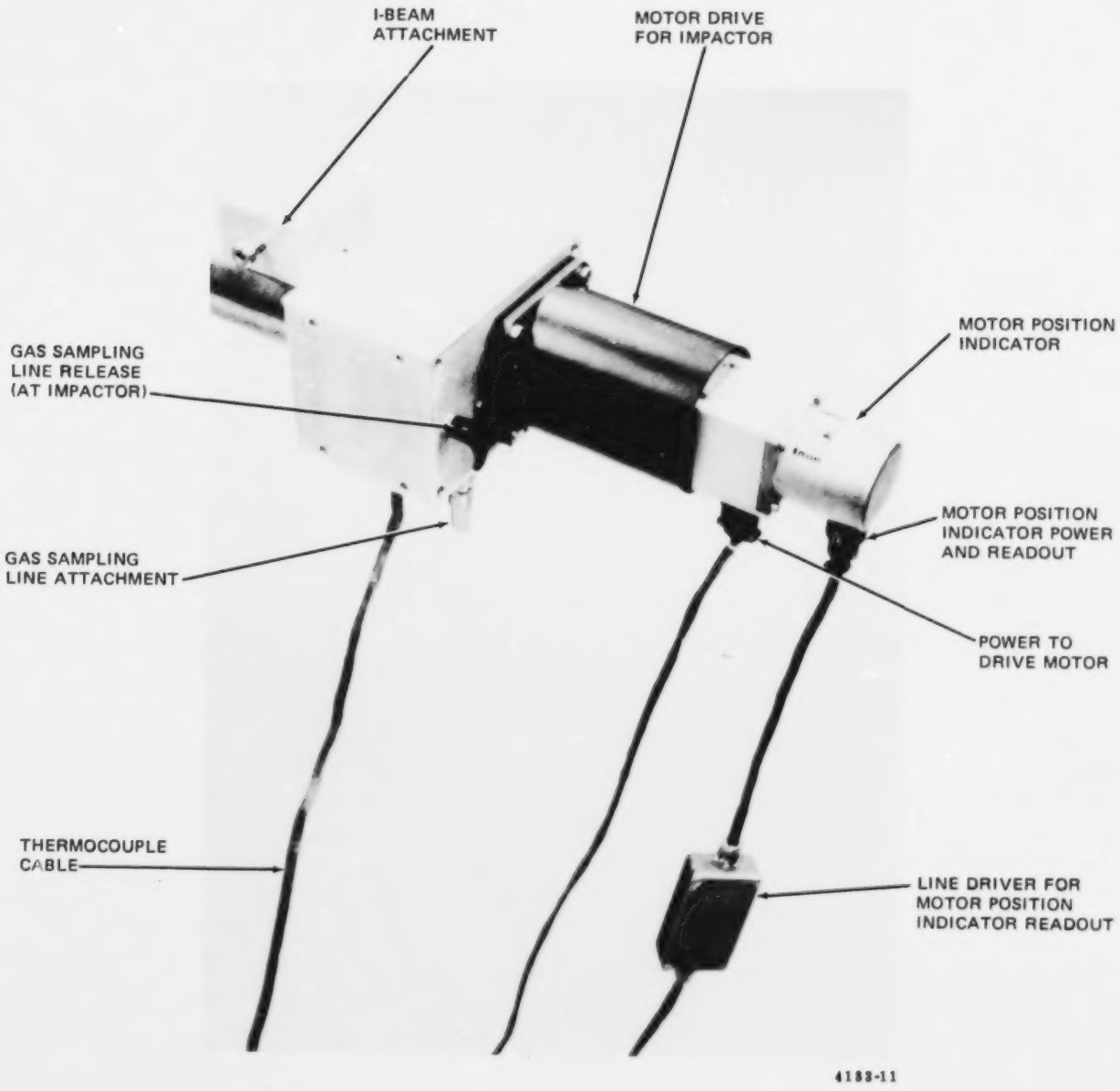


Figure 3. Rear end of probe showing various component parts.

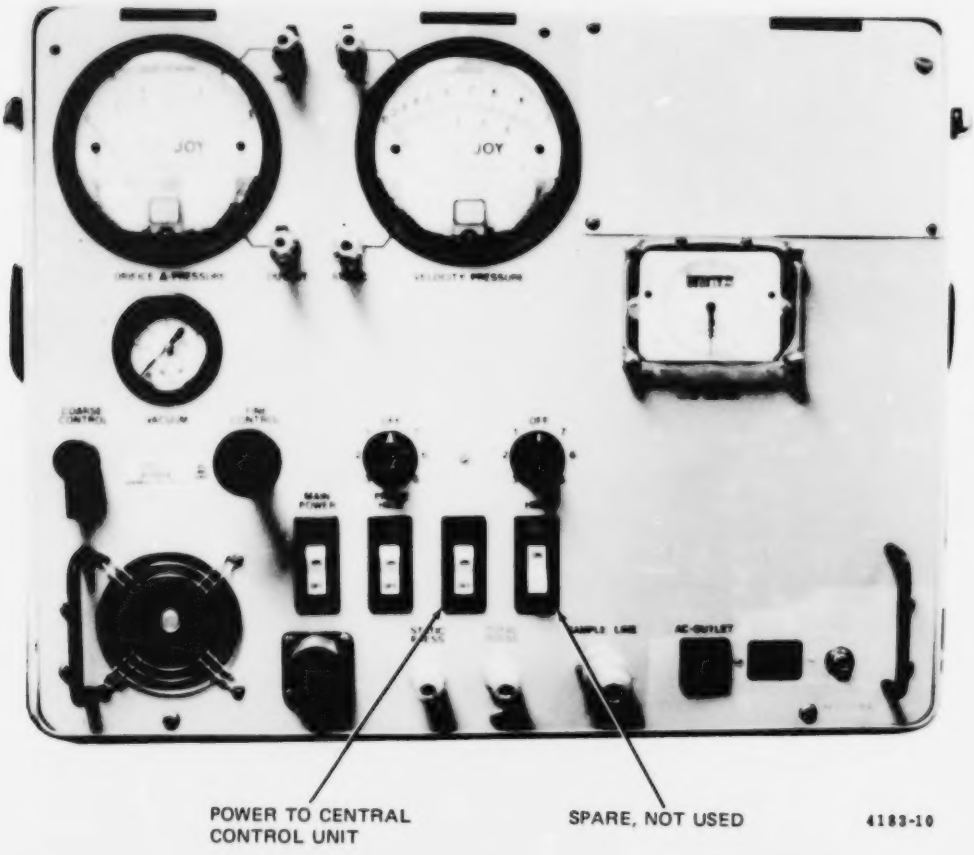


Figure 4. The modified Andersen EPA control unit.

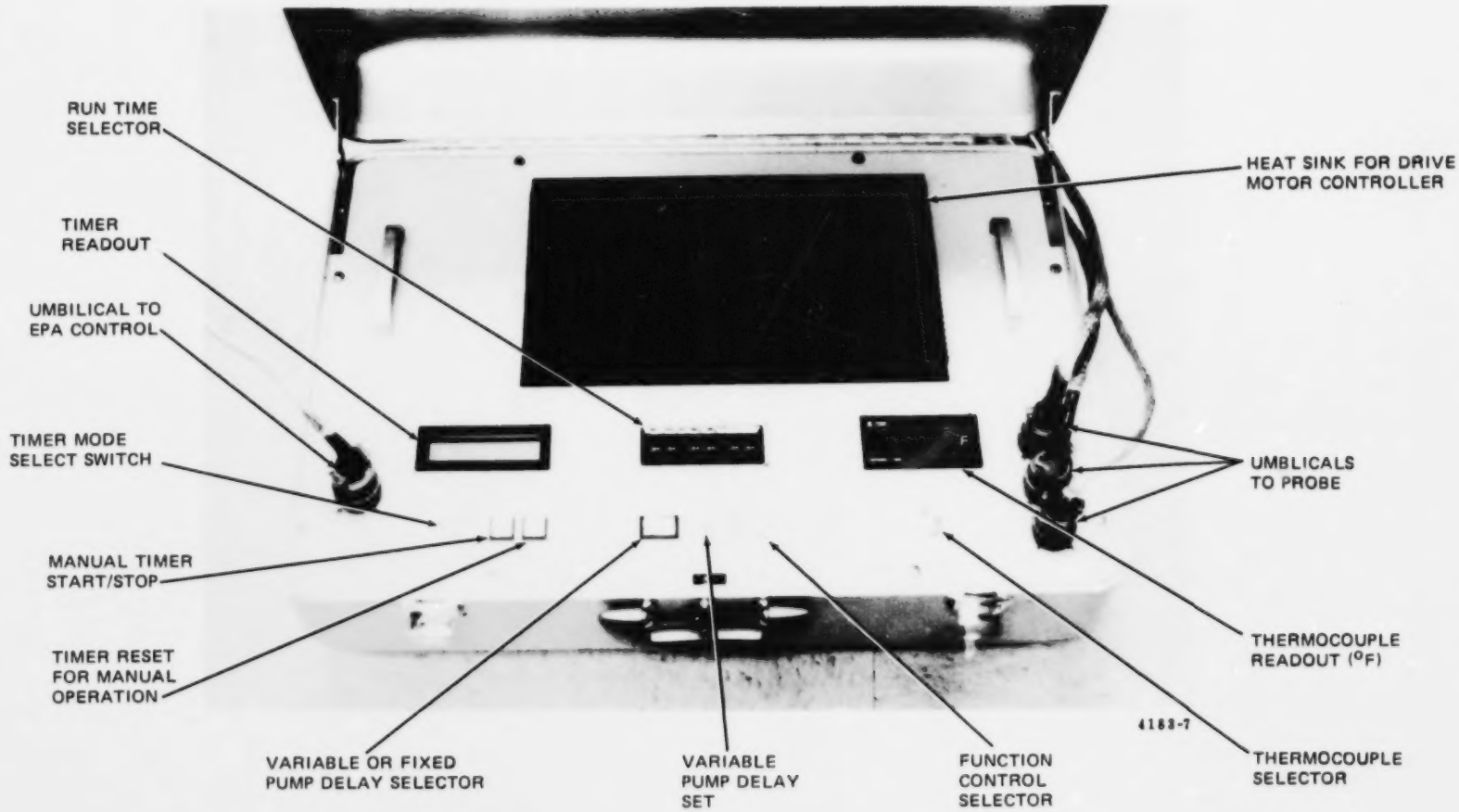


Figure 5. The central control unit.

SECTION IV

CALIBRATION STUDIES

A prototype impactor was constructed early in the project. The prototype is a single stage slit impactor with a drum upstream and downstream of the jet. The upstream drum is fixed and the downstream drum is connected to an oscillating electric motor through a pressure seal. The slit jet is designed so that various slit widths and jet to plate spacings can be used. The impaction substrate used in the calibration studies was a thin coating of petroleum jelly applied directly to the collection drum.

The first study conducted with the prototype was a study of the uniformity of the particle deposition pattern. Figure 6 shows a diagram of the experimental apparatus.

The particle deposition pattern on the collection drum of the breadboard impactor was checked by sampling an ammonium fluorescein aerosol. A solution of ammonium fluorescein was made by dissolving one gram of fluorescein in 20 ml of ammonium hydroxide. The solution was then diluted 20:1. A small amount of solution was placed in a DeVilbiss medical nebulizer and dispersed into a plenum. The impactor samples the particles at the rate of 28.3 LPM from the bottom of the plenum. A jet width of 0.2 mm and a jet to plate spacing of 0.5 mm was used. The deposition pattern observed was uniform with no irregularities. The use of fluorescent particles during this phase of the study also facilitated a qualitative investigation of wall losses within the impactor. Slight particle deposition (<2%) was noted on the jet housing at each end of the jet. No other significant deposition was detected.

A second set of experiments were conducted with the prototype to measure collection efficiency as a function of slit width and jet to plate spacing.

Figure 7 shows a diagram of the calibration apparatus used for making collection efficiency measurements with the prototype. As this figure shows, a Climet Instruments Model 208 optical particle counter in conjunction with a Canberra Series 30 multichannel analyzer was used to measure aerosol concentration upstream and downstream of the prototype. Collection efficiency was determined by comparison of the two concentration measurements.

Two slit widths and two sizes of monodisperse aerosols were used in the calibration study. The slit widths were 0.315 mm (12.4 mils) and 0.787 mm (31 mils) and the particle sizes used were 1.099 micrometers and 2.02 micrometers. Dow Polystyrene Latex and Polyvinyltoluene Latex monodisperse suspensions were dispersed to generate the aerosols.

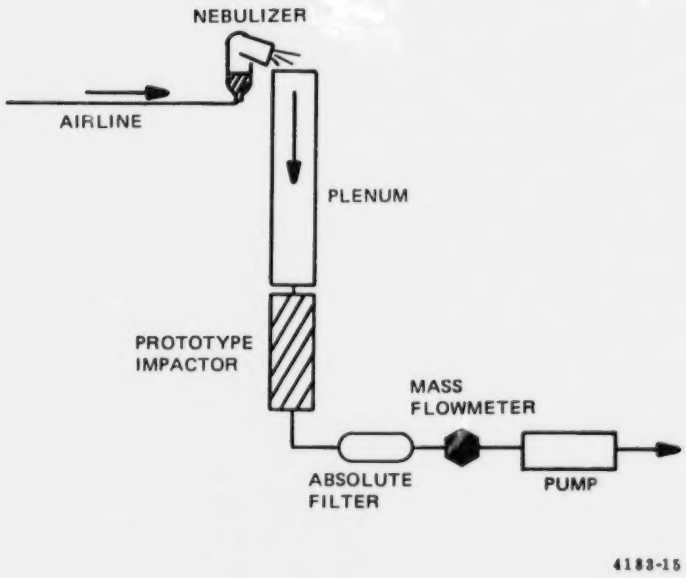


Figure 6. System to determine particle deposition in the prototype impactor.

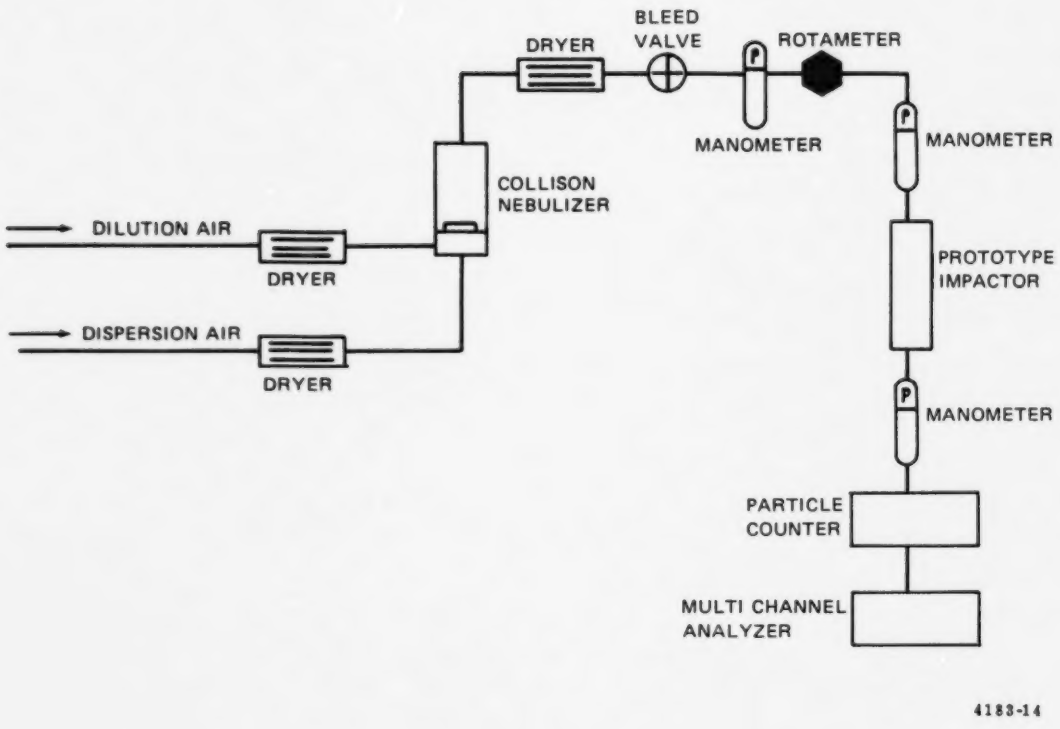


Figure 7. System to study the collection efficiency and D_{50} of the prototype impactor for different slit widths and jet-to-plate spacings.

During tests with 2.02 micrometer diameter aerosols, particle impaction losses made necessary the removal of the rotameter. It was replaced with a length of stainless tubing with pressure taps on either end. Pressure drop across the tube was correlated to flow by making a series of flow-pressure drop measurements with the tube mounted in series with an NBS traceable laminar flow element calibration device. With the tube in the system, flowrate was measured by noting the pressure drop across the tube.

Tables 2 and 3 summarize the calibration data. In each table, data are presented in the order taken. Tables 3 and 4 are data for the same configuration taken approximately two weeks apart. The data shown in Table 2 were taken during the two week span. Figures 8 and 9 show collection efficiency as a function of the square root of the Stokes number, STK.[5] The data from Tables 3 and 4 are plotted on the same figure, Figure 9. Marple's theory[5] predicts a value of 0.73 for STK for a slit nozzle configuration at 50% collection efficiency. The measured value from the prototype stage compare well with the theoretical value (0.72 vs. 0.73). The data from Table 4 do not agree well with the other results. Comparison of the stage pressure drops in Table 4 with those in Table 3 indicates that either the flows were measured erroneously or that the impactor slit width was not properly reset for the runs shown in Table 4.

From this study we concluded that the intended design would perform as predicted by Marple's theory.[5] Therefore, we proceeded with the design of the in-stack unit selecting jet widths according to slit impactor theory. The pertinent interior dimensions of the in-stack unit are given in Table 5.

Table 2. Collection Efficiency and $\sqrt{STK}$ for a 1.099 micrometer Polystyrene Latex Aerosol. Jet Width: 0.315 mm, Jet to plate spacing: 1.016 mm, Jet Length: 3.1 cm

Flowrate (liters/min)	Average Collection Efficiency (%)	Standard Deviation (%)	$\sqrt{STK}$
5.7	16.0	1.3	.515
7.1	8.3	1.8	.576
8.5	12.5	5.8	.631
9.9	21.0	1.7	.682
10.5	44.1	3.1	.701
11.3	65.4	0.1	.729
12.2	76.7	0.5	.756
12.7	92.4	0.5	.773
14.2	97.2	0.1	.815
12.7	93.3	0.1	.773
11.3	58.8	0.8	.729
11.0	60.3	1.9	.719
10.8	47.4	0.7	.711
8.5	3.3	2.1	.631

Table 3. Collection Efficiency and $\sqrt{STK}$ for a 2.02 micrometer Polyvinyltoluene Aerosol. Jet Width: 0.787 mm, Jet-to-plate Spacing: 2.286 mm Jet Length: 3.1 cm. Data set I

Flowrate (Liters/min)	Average Collection Efficiency (%)	Standard Deviation (%)	ΔP across Impactor (cm w.c.)	$\sqrt{STK}$
12.7	20.4	2.4	0.64	0.553
14.6	34.4	1.6	0.76	0.592
16.1	34.7	5.7	0.89	0.622
17.8	32.6	2.8	1.3	0.654
19.5	43.1	0.8	1.6	0.685
21.5	41.2	2.1	1.9	0.719
23.2	58.7	0.8	2.3	0.747
24.6	66.5	0.5	2.7	0.769
26.6	83.3	0.5	3.2	0.799
28.3	95.3	0.2	3.7	0.824
30.0	98.2	0.1	4.0	0.849

Table 4. Collection Efficiency and $\sqrt{STK}$ for a 2.02 μm Polyvinyltoluene Aerosol.
Jet Width: 0.787 mm, Jet-to-Plate Spacing: 2.286 mm
Jet Length: 3.1 cm. Data Set II

Flowrate (Liters/min)	Average Collection Efficiency (%)	Standard Deviation (%)	ΔP across Impactor (cm w.c.)	$\sqrt{STK}$
9.9	30.7	4.4	0.25	0.488
11.3	26.8	1.2	0.25	0.521
12.7	25.4	0.8	0.51	0.553
14.2	34.3	2.6	0.76	0.583
15.6	34.4	2.8	0.76	0.611
17.0	35.6	3.6	1.0	0.639
18.4*	52.9	0.3	1.0	0.665
19.8*	57.3	0.8	1.3	0.690
22.2*	60.0	1.6	1.3	0.714
22.7*	65.4	2.1	1.5	0.738
24.1*	63.6	1.6	1.8	0.760
25.5*	73.8	0,5	2.0	0.782
26.9*	78.7	0.8	2.3	0.803

*Drum not oscillating.

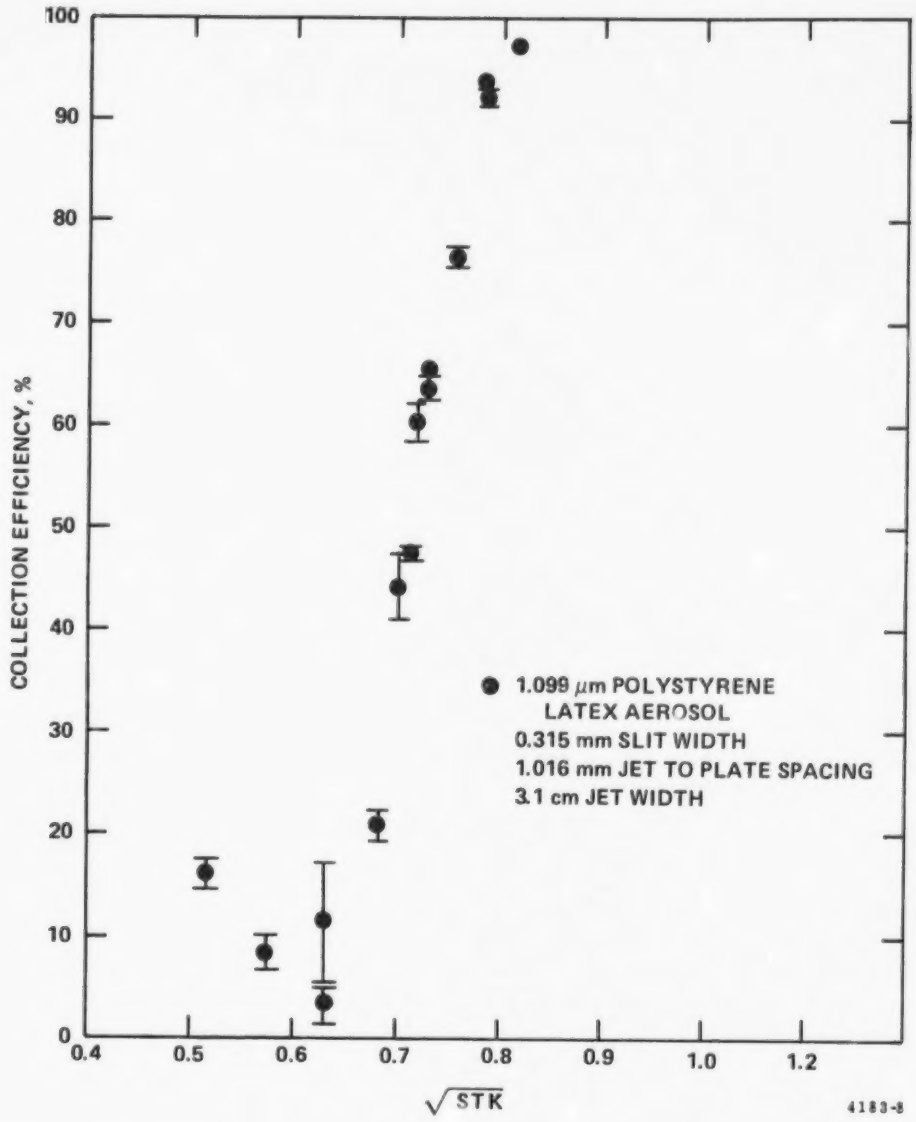


Figure 8. Collection efficiency versus $\sqrt{STK}$ for a 1.09 micrometer polystyrene latex aerosol. Results from Table I.

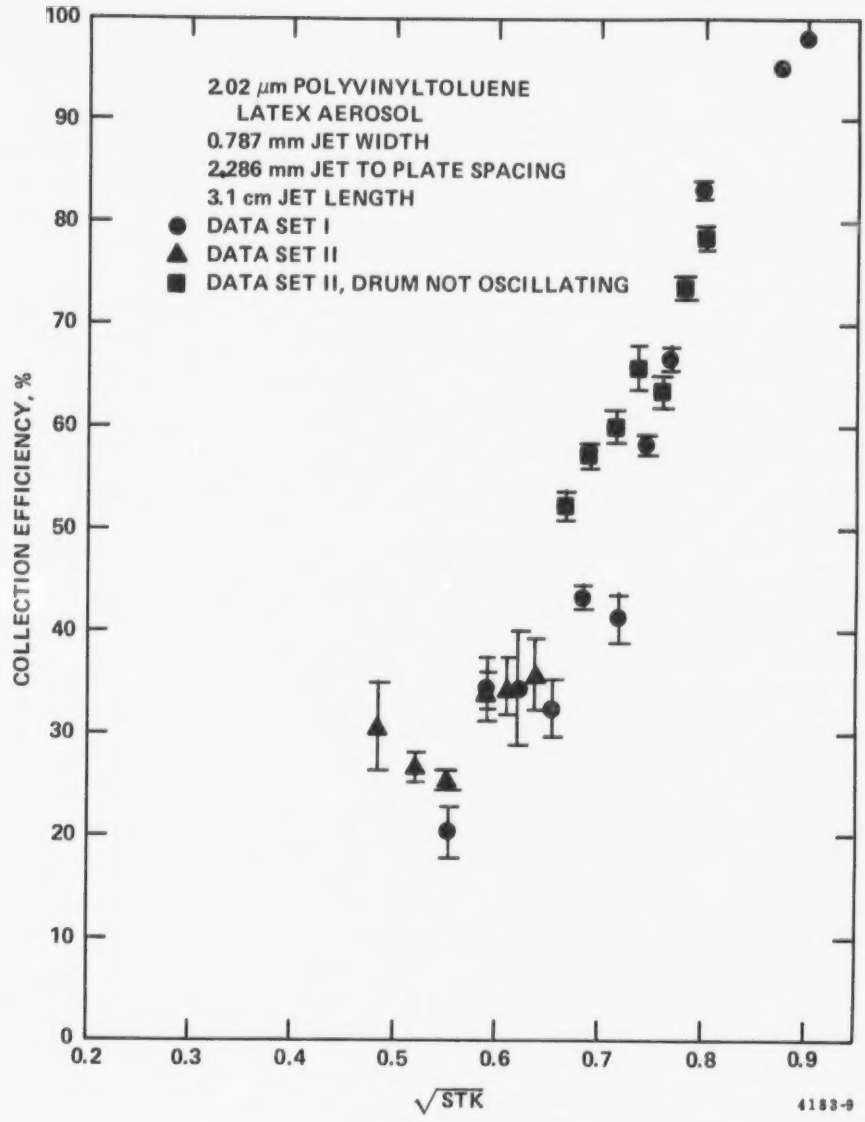


Figure 9. Collection efficiency versus $\sqrt{STK}$ for 2.02 micrometer polyvinyltoluene latex aerosol. Results from Table II and III.

Table 5. Interior Dimensions of the In-Stack Impactor*

Stage	Aerodynamic D_{50} (micrometers)	Slit Width (mm)	Jet-to-Plate Spacing (mm)
precutter	14.9	--	
1	8.0	2.64	5.46
2	4.0	1.35	2.79
3	2.0	0.686	1.52
4	1.0	0.356	1.14
5	0.5	0.188	0.89

*Design flowrate = 22.65 lpm (0.8 cfm) at 150°C (302°F).
Slit length is 31mm for all stages.

SECTION III

SUBSTRATE DEVELOPMENT

Shortly after project initiation we were advised by the project officer that the most common greases, Apiezon H, L, M, and N, that were currently in use as impaction substrate coatings[6] were not suitable for this work. This is because these greases contain unacceptably high amounts of metals which are expected to occur in trace quantities in typical samples to be obtained with the impactor. Therefore, other substrate coatings were investigated.

After consulting with experts in polymer chemistry in the Membrane and Fibers Section of the Applied Sciences Research Department at Southern Research, work began on the selection of a chemically stable, high melting point polymer as a substrate coating and substrate materials which would be compatible with the coatings.

Table 6 lists the potential substrate materials which were found. These materials were chosen because they would be compatible with potential substrate coatings, are unaffected by high temperatures and are essentially inert. Mylar and Kapton were chosen for substrate materials. Mylar is the first choice because it has a much lower x-ray background than Kapton, especially for sulfur.

After evaluating the adhesion properties of a number of polymers on mylar and Kapton substrates, six were chosen for testing as impaction media at various temperatures. The six compounds are listed in Table 7.

Mylar and Kapton substrates were coated with the six polymers by two techniques, a spin casting technique and dipping, both of which leave a uniform thin coating on the substrate. The Vynathenes and DuPont polyester materials are soluble in Methyl Ethyl Ketone. The spin casting technique uses a rapidly spinning cup with the substrate held on the inside of the cup. A solution of the substrate coating is poured into the cup while the cup is rotating, with the rotation continuing until the solvent has evaporated. An alternative coating method used later was to spray coat the substrate using a small airbrush.

In order to determine the suitability of the polymer coatings as impaction substrates, the system shown in Figure 10 was used. A Collison nebulizer redispersed 2.02 micrometer polyvinyltoluene latex (PVTL) spheres. An optical particle counter in conjunction with a multichannel analyzer (MCA) was used to measure the concentration of the PVTL particles upstream and downstream of the impaction stage. The collection efficiency was determined by comparing the two concentration measurements.

Table 6. Possible Substrate Materials for the Impactor

Identity and Composition	Chemical Characterization
Mylar (Du Pont) Polyethylene terphthalate (linear polymer)	Fusible, M.P. 250°C, softening pt. is 230°C. Solvent swelling by Ketones, Aromatics, Alcohols, Dioxane. Attacked by alkali, some acids (as HCl).
Kapton H (Du Pont) - Polyimide Polycondensation between an aromatic tetrabasic acid and an aromatic amine. (May be combined with Teflon FEP resin to make a heat sealable structure).	Infusible. No known organic solvents. High temperature stability: 200°C+. Subject to slow oxidation degradation.
Tedlar (Du Pont) - polyvinyl fluoride. Contains 0.05 to 1.0 wt % of dimethyl acetamide residual	Heat sealable @ ∿200°C. Resists solar degradation. Partially soluble in a few polar solvents above 300°F. Compatible with adhesives: acrylics, polyesters, epoxies, rubber.
Kynar (3M) - polyvinylidene fluoride	Heat sealable @ 190°C, M.P. 158°C, High temperature stability 140°C. Similar to Tedlar properties.
Lexan (GE) polycarbonate	Heat sealable @ 135°C. Softening temperature 125°C. Soluble in chlorinated hydrocarbons. Partially soluble by aromatics, ketones and esters (act as stress-crazing agents).
Polysulfone (U.C.)	Melting Temperature 300°C, softening temperature 235°C. However, presence of $-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-$ group expected to interfere in X-ray measurements.

Table 7. Substrate Coatings

Coating	Composition: % Vinyl Acetate	% Ethylene	Ring and Ball Softening Point	Flow-Melt Point
EY903*	45%	55%	144°C (292°F)	-
EY904*	47%	53%	132°C (270°F)	-
EY906*	55%	45%	129°C (265°F)	-
EY907*	60%	40%	158°C (316°F)	-
49032**	-	-	-	110°C (230°F)
49000**	-	-	-	130°C (266°F)

*Vynathenes, U.S. Industrial Chemicals

**Polyester, DuPont

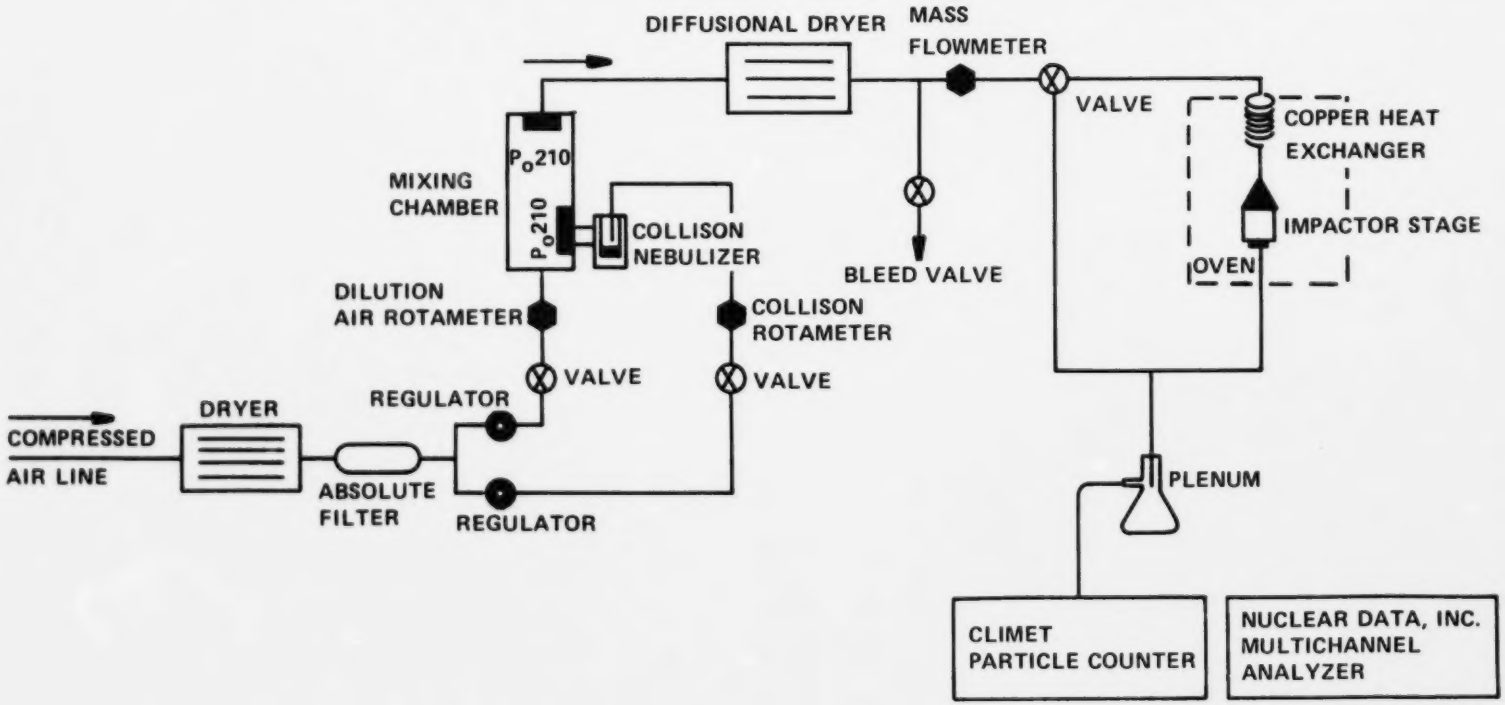


Figure 10. System to determine the collection efficiency of candidate substrate materials. 4183-13

Samples of the candidate substrates were cut to fit a Brink BMS-11 impactor collection plate. A flowrate and jet diameter combination was chosen such that 2 μm PVTL particles would have an imapction efficiency near 100%, but the jet velocity would be high enough to result in significant losses due to particle bounce when no adhesive coating was used on the substrate. Velocities on the order of 35 m/s and 70 m/s were used.

Many of the candidate materials did not appear to be effective in reducing particle bounce when tested at ambient temperatures 20°C). Subsequently, collection efficiency measurements were made at 93°C by placing the impactor stage in an oven. Preliminary tests on several substrates showed that the efficiencies increased slightly. A copper heat exchanger was then added to the system so that the aerosol would equilibrate to 93°C before passing through the impactor. Collection efficiency improved substantially with all spun cast substrates, but did not for the dipped substrates, which had much thinner coatings than the spin coated substrates.

Glass fiber, bare metal, vaseline, and Apiezon L were used as control substrates and the efficiency for each was periodically checked. All collection efficiencies are listed in Table 8.

Weight stability was determined for each substrate at progressively higher temperatures. The results of these tests are shown in Table 9.

After reviewing the behavior of the polymer coatings as impaction substrates and their stability at elevated temperatures we concluded the best material was the EY907 Vynathene on mylar. Later field tests indicated that amorphous polypropylene (supplied by Hercules, Inc.) and butyl rubber (Exxon 065) are also acceptable materials. The butyl rubber coating will permit operation to temperatures of 200°C (the maximum impactor temperature limit because of certain teflon components).

Retention of impacted particles is always a problem in the application of cascade impactors. The design and operating mode of the XRF compatible impactor minimizes this problem as compared with all conventional designs. Because the impaction surface is in constant, rather rapid, motion beneath the jet the incoming particles generally are impacted on fresh coating material instead of material covered over by previously impacted particles. In order to insure that incoming particles have a good probability of impacting on an unused area we suggest that the total projected area of the particles collected on a given substrate be limited to a value no gerater than 50% of the total area swept by the slit. Stage loadings at 50% coverage are given in Table 10 in terms of both total catch weight in milligrams and in units of micrograms per square centimeter. These loadings are for unit density spheres, if the true particle

Table 8. Collection Efficiencies of Copolymer/Thin Film Substrates

SAMPLES SPUN CAST AT 3500 RPM. FILMS ~ 0.005 cm THICK. DRY COATING ~ 0.0013 cm THICK.												Dipped Samples, Each Layer ~18-20Å 1-5 Layers, 2-25 Layers, 3-10 Layers.			CONTROL SUBSTRATES			
EY903/ Mylar	EY903/ Kapton	EY904/ Mylar	EY904/ Kapton	EY906/ Mylar	EY906/ Kapton	EY907/ Mylar	EY907/ Kapton	49032/ Mylar	49032/ Kapton	49000/ Mylar	49000/ Kapton	EY903/ Kapton[1]	EY903/ Kapton[2]	49032/ Kapton[3]	Glass Fiber	Vase-line	Bare Metal	Apiezon L
CONDITIONS: Samples tested with the second stage of a Brink BMS-11 Impactor at ambient																		
68%	55%	59%	62%	52%	48%	52%	49%	57%	57%	-	-	61%	60%	68%	-	98%	54%	-
CONDITIONS: Samples tested with the first stage of a Brink BMS-11 Impactor at ambient																		
67%	56%	67%	65%	74%	71%	80%	62%	46%	39%	63%	46%	52%	50%	52%		96%	74%	77%
																95%	46%	87%
																95%	89%	
																	57%	
																	66%	
																	64%	
															Averages	95%	66%	82%
CONDITIONS: These samples were tested with Stage 1 at 93°C (200°F)																		
76%	77%	72%																
64%	73%	73%	66%	76%													37%	
85%	73%	65%	66%	80%													42%	
	65%																29%	
																	29%	
Averages																	36%	
75%	72%	70%	66%	78%													12%	
																	31%	
CONDITIONS: These samples were tested with Stage 1 at 93°C. A copper heat exchanger was added to system so as to allow aerosol time to heat to 93°C.																		
87%	93%	94%		81%	84%	89%	91%	87%	87%	75%	58%	Sample	40%	60%	63%		59%	83%
89%	87%	92%	82%	83%	91%	96%	94%	57%	86%	79%	46%	Supply	45%	65%	72%		71%	78%
83%	88%	84%	81%	74%		97%	87%	85%	84%		63%	Depleted	69%	40%	57%		54%	71%
								85%		73%			26%	40%	61%		30%	87%
								56%					87%	58%	64%		46%	
								62%							65%		55%	
															42%			
Averages															65%			
86%	89%	90%	81.5%	79%	87.5%	94%	91%	72%	86%	76%	59%		53%	53%	45%			
															59%		52.5%	80%

Table 9. Weight Stability of Substrates

SAMPLE	INITIAL WEIGHT (mg)	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS	INITIAL WEIGHT (mg)	WEIGHT AFTER BAKING (mg)	WEIGHT DIFFERENCE (mg)	BAKING CONDITIONS
EY903/ MYLAR	52.77	52.72	0.05	2 hrs @ 121°C	52.72	0.00	4 add'l hrs @ 121°C	52.71	0.01	2 hrs @ 149°C	52.73	-0.01	2 add'l hrs @ 149°C	52.73	0.00	2 hrs @ 177°C	51.52	1.21	4 hrs @ 177°C	51.53	51.02	0.51	2 hrs @ 204°C
EY903/ KAPTON	52.18	52.05	0.13		52.05	0.00		51.96	0.09		51.93	0.03		51.80	0.07		51.33	0.47		51.33	50.97	0.36	
EY904/ MYLAR	50.91	50.89	0.02		50.89	0.00		50.89	0.00		50.88	0.01		50.68	0.20		50.37	0.31		50.37	50.18	0.19	
EY904/ KAPTON	53.26	53.15	0.11		53.13	0.02		53.04	0.09		53.00	0.04		52.90	0.10		52.70	0.20		52.70	52.23	0.47	
EY906/ MYLAR	54.05	54.02	0.03		54.03	-0.01*		54.03	0.00		54.02	0.01		53.71	0.31		53.26	0.45		53.37	53.09	0.18	
EY906/ KAPTON	56.86	56.73	0.13		56.71	0.02		56.62	0.09		56.56	0.06		56.50	0.06		56.16	0.34		56.15	55.43	0.72	
EY907/ MYLAR	51.77	51.71	0.06		51.72	-0.01		51.70	0.02		51.72	-0.02		51.68	0.04		51.38	0.30		51.38	51.12	0.26	
EY907/ KAPTON	51.25	51.14	0.11		51.10	0.04		51.00	0.10		50.98	0.02		50.91	0.07		50.73	0.18		50.72	49.92	0.80	
EY903† KAPTON	12.86	12.85	0.01		12.85	0.00		12.85	0.00		12.85	0.00		12.85	0.00		12.84	0.01		12.85	12.83	0.02	
EY903/ KAPTON	20.38	20.36	0.02		20.36	0.00		20.35	0.01		20.36	-0.01		20.35	0.01		20.35	0.00		20.35	20.33	0.02	
49032/ KAPTON	39.16	39.12	0.04		39.09	0.03		39.08	0.01		39.10	-0.02		39.10	0.00		39.08	0.02		39.08	39.06	0.02	
49032/ MYLAR	56.09	55.91	0.18		55.89	0.02		55.86	0.03		55.87	-0.01		55.85	0.02		55.82	0.03		55.82	55.55	0.27	
49032/ KAPTON	61.05	60.89	0.16		60.77	0.12		60.64	0.13		60.62	0.02		60.42	0.20		60.19	0.23		60.19	59.60	0.59	
49000/ MYLAR	46.66	46.65	0.01		46.64	0.01		46.62	0.02		46.62	0.00		46.61	0.01		46.58	0.03		46.59	46.56	0.03	
49000/ KAPTON	50.38	50.35	0.03		50.36	-0.01		50.33	0.03		50.35	-0.02		50.32	0.03		50.23	0.09		50.24	50.19	0.05	

† Dipped substrates. Each layer is 38-20A': 1-5 layers, 2-25 layers, 3-10 layers.

* Negative sign is indicative of weight gain.

Table 10. Maximum Stage Loadings

Stage	Particle dia., μm	Maximum catch, mg	μm/cm^2 at 50% converse
1	12	3.85	400
2	6	1.92	200
3	3	0.96	100
4	1.5	0.48	50
5	0.75	0.25	25

*Unit density particles

density is greater than 1 g/cm^3, the loadings in Table 10 can be multiplied by the square root of the specific gravity of the particles. That is, 1.4 times as much material can be collected on each stage if the particle density is 2.0 g/cm^3. Experience has shown that the adhesion characteristics of fine particles is generally greater than that of coarse particles; so satisfactory performance might be obtainable with the last two stages with more than a monolayer thickness of deposited particles. In which case the values quoted for the last two stages might be safely exceeded by a factor of two to four (complete coverage to two layers of particles). Because the values quoted in Table 10 are effectively based on a monolayer of particles there is no advantage to be gained in restricting the stages which collect the larger particles to a maximum surface loading of 200 micrograms per square cm.

SECTION IV

DESCRIPTION OF THE IMPACTOR

The impactor was described briefly in the Introduction. Here a more detailed account of its operation is presented along with assembly/disassembly instructions.

As Figure 1 shows, the impactor is a five stage device with an integral back up filter. One of the oscillating drums which holds the collection substrates is shown in Figure 11. The locating pins and tabs which secure the edges of the 47 mm diameter substrate are indicated. The punch which was designed to cut the collection substrates from sheet mylar also punches out small holes for the locating pins. Figure 12 shows the back-up filter assembly which slides in and out of the rear of the top shell of the impactor. It breaks apart into halves allowing the back-up filter to be easily installed or removed. As shown in Figure 2, the impactor requires attachment to a sampling probe which provides connection to the drive for the stages, a heated gas sampling line, and thermocouple sensors in the gas stream, impactor, and probe. Figure 13 shows the end of the impactor which attaches to the probe. This figure, and Figure 14, which shows the end of the probe where the impactor attaches, illustrate how the impactor fits onto the probe. Male dovetails on the end of the probe engage female dovetail slots machined in the rear of the impactor. The arrangement of the dovetails allows only one orientation for the impactor-probe assembly. Figures 13 and 14 also show thermocouple, gas sampling and drive connections on the probe and impactor. The thermocouple connections must be made before the impactor is mounted on the probe; other connections to the probe are made automatically when the impactor is properly seated. Allen screws located in dovetail slots on the impactor are backed out through mating threaded holes in the male probe dovetails to secure the impactor, and are left flush with the surface of the probe.

When the impactor is properly seated on the probe a quick connect gas sampling fitting is automatically secured. For disassembly this connection is broken by pulling on the "T" handle at the rear of the probe (see Figure 3), turning the handle a quarter turn and then pushing the handle. Pulling on the "T" handle while the impactor is secured to the probe will not result in any leakage or break in the connection since there is no free room for disconnection while the impactor is bolted to the probe.

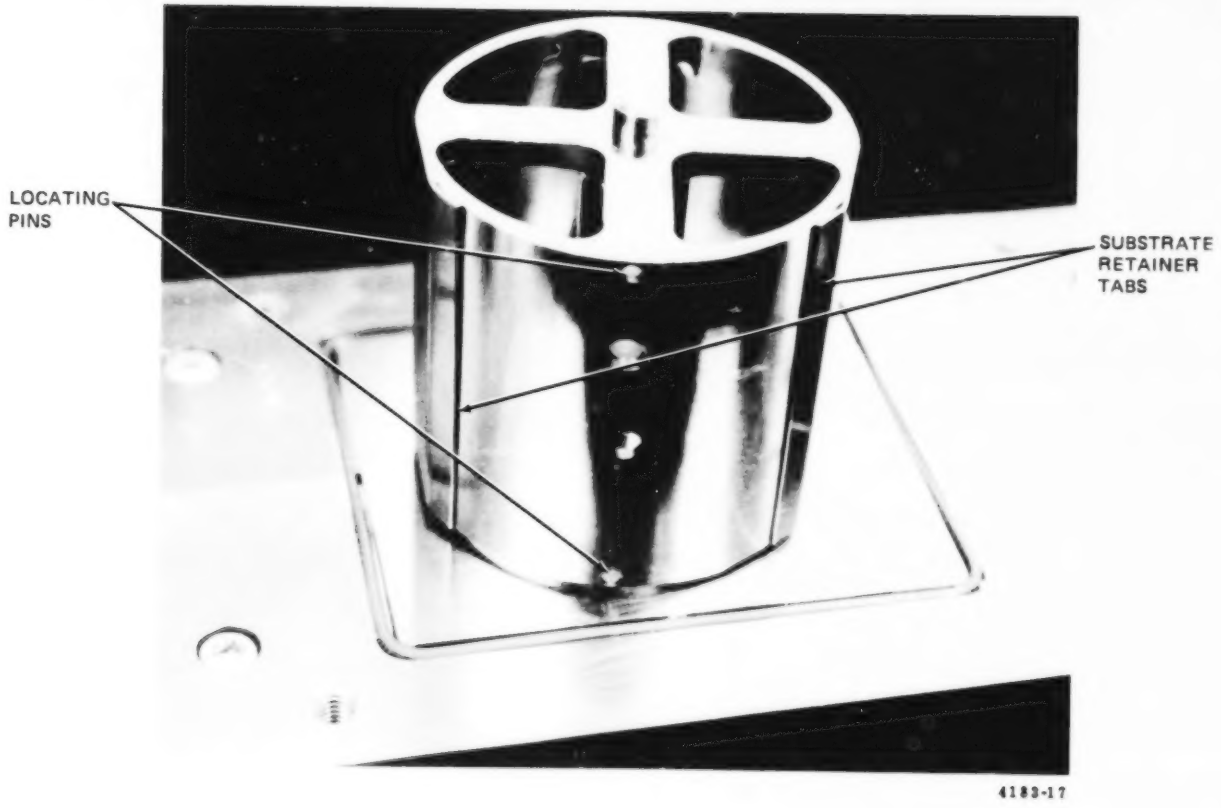


Figure 11. Typical collection drum showing the substrate locating pins and retaining tabs.

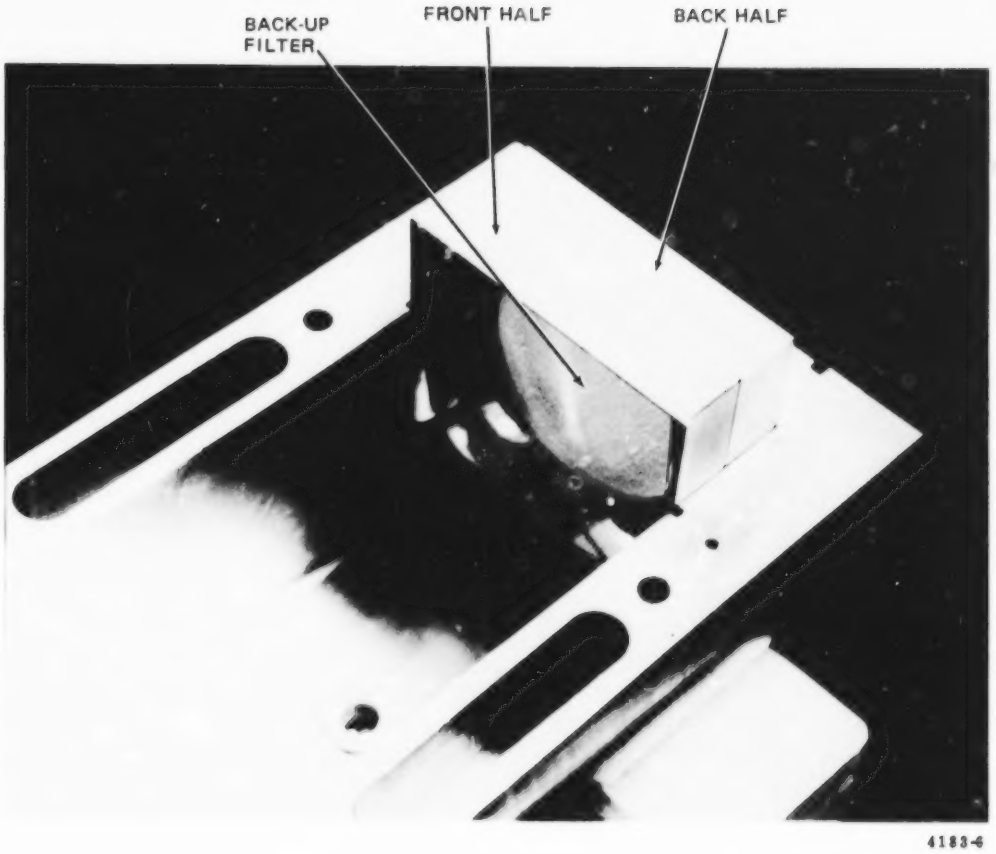


Figure 12. Back-up filter assembly.

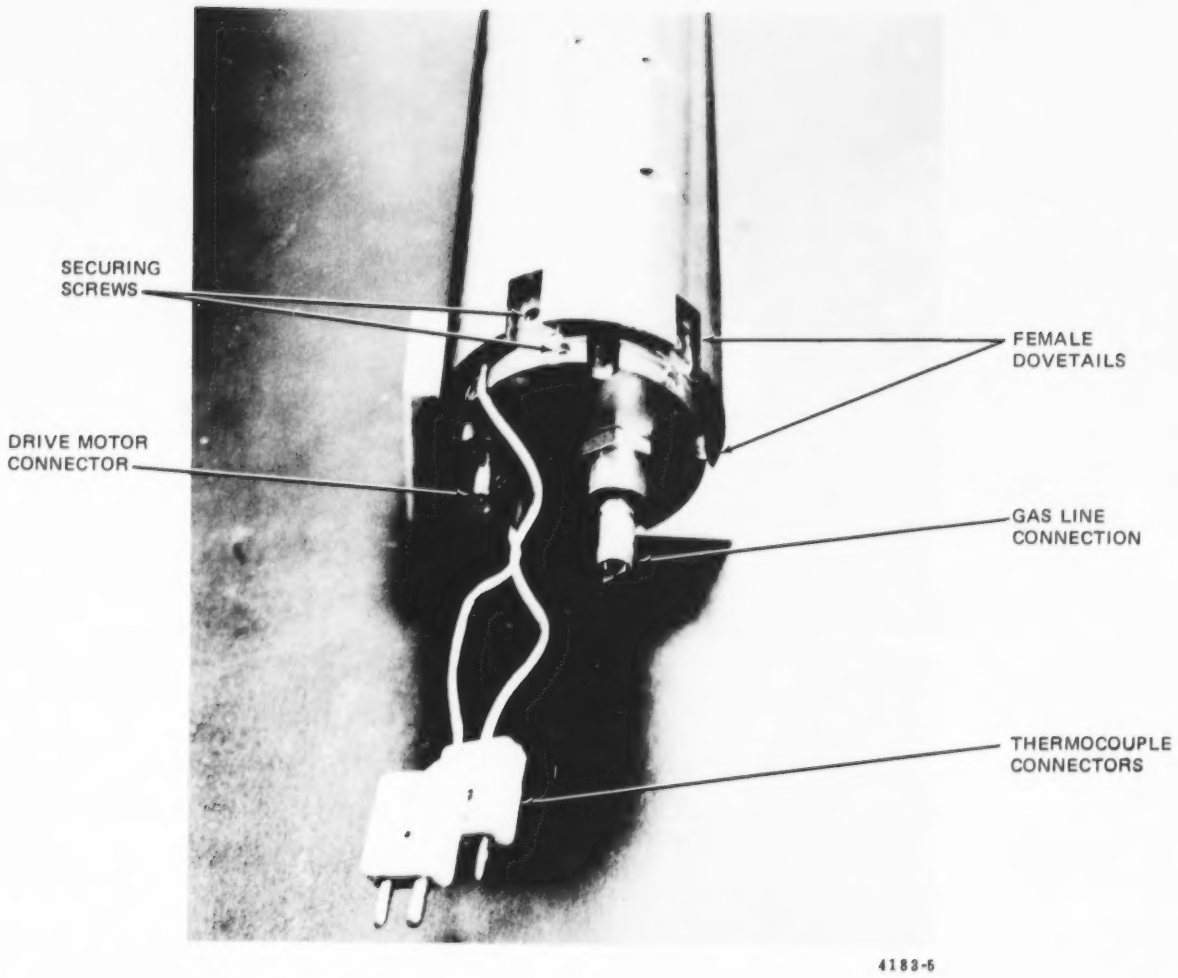


Figure 13. End of impactor showing attachment points for the probe, gas line connection, thermocouple connectors and drive connection.

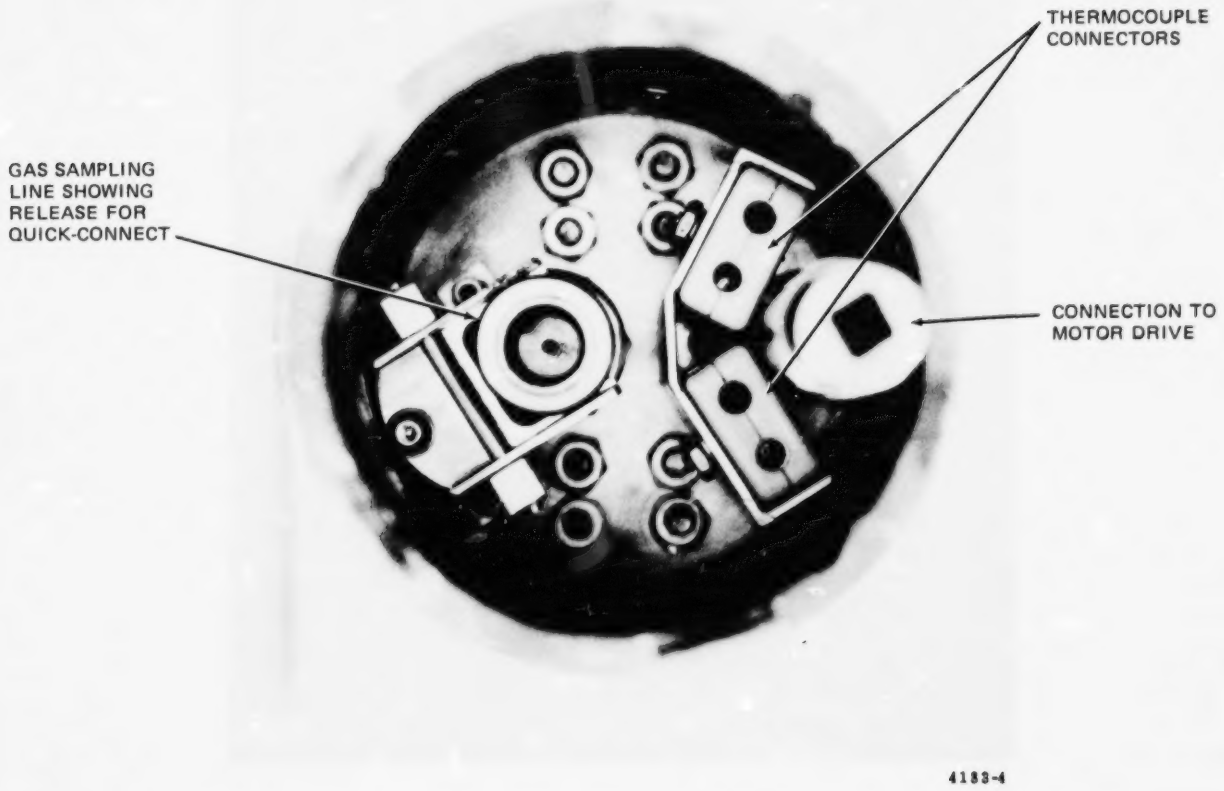


Figure 14. End of probe showing gas line connection and release, thermocouple connector and drive connection.

Disassembly and Assembly of the Impactor

Disassembly and assembly of the impactor is carried out with the impactor removed from the probe. The first step in disassembly is to remove the 12 bolts holding the top shell of the impactor to the bottom half (Figure 15). Second, remove the three bolts on either end of the impactor which hold the inlet and exit transforms to the top shell (Figures 16 and 17). Third, loosen the two bolts which secure the inlet transform to the lower half of the impactor. Finally roll the impactor over and lift the lower half up and off of the upper half leaving the upper half on the workbench. Potential damage to substrates can be eliminated by replacing some of the 12 top to bottom half securing bolts with threaded rods about 6 inches long. These rods will keep the two halves from hitting during disassembly or assembly.

When this stage of disassembly is reached the substrates and back-up filter can be removed or replaced. The impactor is then reassembled and rebolted. During assembly each bolt should be checked to be sure it is coated with anti-seize compound (for example, Silver Goop®). If anti-seize compound is not used on all threaded connections, then galling will almost certainly result.

The impactor is then re-attached to the probe, as described earlier in this section, and it is ready to use for sampling. Since the probe is quite heavy it is anticipated that it will remain on the sampling platform attached to the I-beam support and the impactor will be mounted and dismounted for each run.

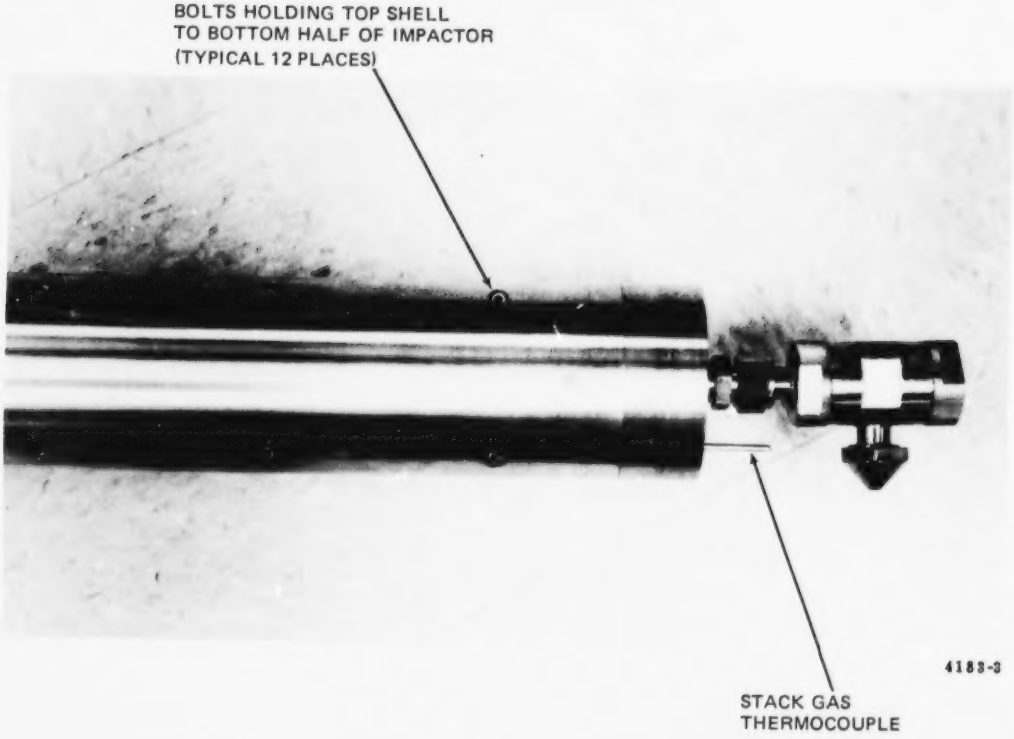


Figure 15. Front of the impactor showing the thermocouple and some of the bolts holding the top shell to the lower half of the impactor.

Figure 16. Exterior view of the inlet transform showing the location of the attachment bolts.

Figure 17. Detail of the exit gas transform showing the location of the bolts which secure the transform to the top shell of the impactor.

SECTION V

SAMPLING WITH THE IMPACTOR

All sampling functions are carried out with the central control unit and the modified Andersen EPA Control Unit. The EPA control unit (Figure 4) has been modified by the removal of the temperature monitor to the central control unit. Main power to all units is provided at the MAIN POWER unit. Main power to all units is provided at the MAIN POWER switch. Power for the central control unit is switched at the third switch from the left, originally used as a vacuum pump on/off switch. The central control unit (Figure 5) controls all sampling and switches the vacuum pump in the EPA unit on and off. Once sampling has commenced, all flowrate adjustment and control is handled with the EPA unit operating as detailed in the operating instructions for the EPA Control Unit.[7]

Once the flowrate has been determined and initial settings have been made, all functions are initiated by the central control unit. The various functions of this unit are shown in Figure 5.

Looking from the left, the first control is the TIMER MODE SELECT switch. There are two positions, AUTOMATIC and MANUAL. The timer is a Intersil ICM7045 complementary MOS Precision Timer chip. The readout for this timer is located above the mode selector and is labelled TIMER READOUT. In the AUTOMATIC mode the timer is used to measure the sampling time and is automatically started and stopped by the FUNCTION CONTROL switch. In the MANUAL mode, the timer is activated by the MANUAL TIMER START/STOP switch and reset by the MANUAL TIMER RESET switch. Four possible functions are possible in the manual operating mode: the standard, sequential, split, and the rally mode. These modes, and the techniques of using each mode, are detailed in the APPENDIX. The appendix reproduces pages 4 and 5 of the Intersil publication on the ICM7045.

The rocker switch to the right of the timer controls is labelled VARIABLE/FIXED PUMP DELAY SELECTOR. This control allows the turn on of the vacuum pump in the EPA Controller Unit to be delayed for up to 30 seconds after the impactor drive has been turned on. The start of the timer is also delayed if the TIMER MODE SELECT switch is in the AUOTMATIC position. The delay time is adjusted with the SET PUMP DELAY potentiometer located between the VARIABLE/FIXED PUMP DELAY SELECTOR switch and the FUNCTION CONTROL switch. If the FIXED PUMP DELAY is selected, then the pump and timer turn on almost instantaneously after the START function is selected.

The main control switch which governs all the motor drive and flow functions is the FUNCTION CONTROL switch. When the main power switch on the EPA Control Unit is turned on, the upper left quadrant of the FUNCTION CONTROL switch is illuminated and the word RESET appears. Depressing the switch once causes the upper right quadrant of the switch to be illuminated and the word START to appear. At this point, pump delays can be selected, the timer mode is set, and the RUN TIME SELECTOR is set for hours, minutes, and seconds of run time. The RUN TIME SELECTOR is programmed by lever switches. The

first two digits are hours (maximum of 99); the second two digits are minutes (maximum of 59); and the third two digits are seconds (maximum of 59). Depressing the FUNCTION CONTROL switch starts the vacuum pump and timer, after any programmed delay, and illuminates the lower left and right quadrants of the FUNCTION CONTROL switch. The lower left quadrant is red and reads ABORT: the lower right quadrant is clear and labelled RUN. If for any reason the run should be stopped before the set run time has elapsed, pressing the FUNCTION CONTROL switch will stop the vacuum pump and leave the TIMER READOUT displaying the elapsed time. If the run proceeds normally, the run time set on the RUN TIME SELECTOR elapses, and the ABORT and RUN lights on the FUNCTION CONTROL switch are extinguished. Pushing the FUNCTION CONTROL switch again has no effect. This was intended so that a completed run would not be ruined. In order to make another run and start the RESET, START, ABORT/RUN sequence again, power to the control unit must be turned off and then back on.

On the right side of the central control unit a Type K digital thermocouple readout is located along with a THERMOCOUPLE SELECTOR switch. Six temperatures can be monitored: STACK, IMPACTOR, PROBE INLET, PROBE OUTLET, GAS METER INLET, and GAS METER OUTLET. The STACK temperature is monitored by a shielded thermocouple which extends through the front of the impactor, shown in Figure 15. The IMPACTOR temperature is monitored in the middle of the impactor out of the gas path. The PROBE INLET and OUTLET and GAS METER INLET and OUTLET temperatures are monitored at the obvious locations. In the case of the probe, temperatures are monitored beneath the heating tape at the surface of the gas line.

SECTION VI

FIELD TRIALS

The completed impactor was tested by sampling four sources at a Kraft paper plant. The sampling at each of the sources was carried out at the sampling locations normally used for compliance testing. Samples were obtained on a Kraft recovery boiler ESP exit, a recovery boiler smelt tank scrubber exit, a lime kiln scrubber exit, and the stack from a partially controlled bark fired power boiler. The flue gas temperatures ranged from 60 to 200°C, and moisture contents ranged from 15 to 50% by volume. The impactor and pre-cutter were heated to a temperature about 20° above the flue gas temperature by means of external heating tapes when sampling at the scrubber exits.

No major difficulties were encountered during the tests. On one occasion, the substrate in the last impaction stage worked out of its retaining clip on one side resulting in the loss of that sample. The ruggedness of the design was demonstrated when a port adaptor broke loose from the port and the impactor end of the probe, with the impactor mounted, fell approximately four feet to the sampling platform grating resulting in only slight cosmetic damage.

Analytical results from the samples were not available in time for inclusion in this report but will be reported elsewhere.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Satisfactory mechanical performance of the completed impactor has been obtained. Limited field trails revealed no major difficulties associated with the operation of the device. The bulk and weight of the system can make transport and use somewhat awkward. A shorter probe would greatly facilitate sampling in many field applicatons of the prototype. A three foot probe was planned in addition to the ten foot probe that was constructed but was not made because of budgetary constraints. The drive system that was used is probably unnecessarily complex and could be simplified by the use of a simple reversible motor controlled by a microswitch.

Although the performance of the device may be predicted adequately from theory, additional calibrations and wall loss measurements are desirable.

APPENDIX

OPERATION OF THE MANUAL TIMER IN THE STANDARD, SEQUENTIAL, SPLIT AND RALLY MODES

FUNCTIONAL OPERATION

STOPWATCH/TIMER OPERATION

The control inputs used in the complete stopwatch application are:

START/STOP	RESET	SPLIT
DISPLAY	STANDARD	RALLY

START/STOP and DISPLAY are designed for connection to single pole double throw switches to insure operation free of contact bounce.

The switch connected to RESET can be a normally open single pole single throw. STANDARD, SPLIT and RALLY are control points with internal pull down resistors to V_{SS}. These are designed to be connected to a rotary function switch which will connect no more than one of these points to V_{DD}. If STANDARD (SPLIT, RALLY) is connected to V_{DD}, the stopwatch is said to be in the STANDARD (SPLIT, RALLY) mode. If all three are left open, the stopwatch is in the SEQUENTIAL mode.

RESET FUNCTION

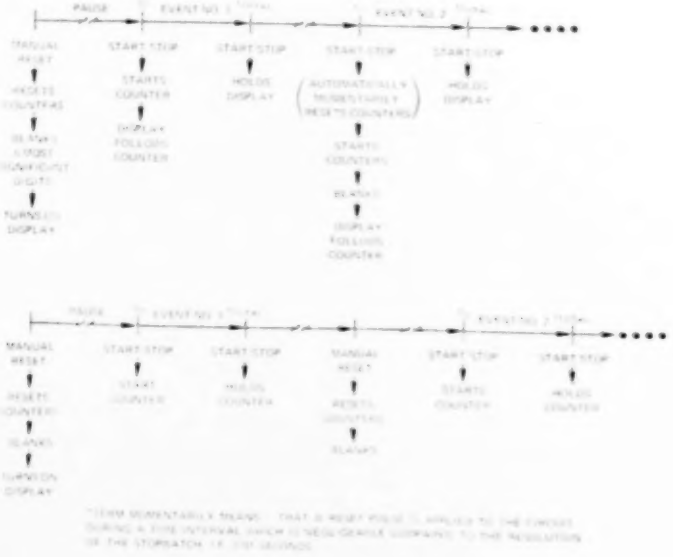
When the stopwatch is turned on, the RESET will normally be activated. This puts the stopwatch in a ready condition by:

1. Resetting all circuitry
2. Blanking seconds, minutes, hours
3. Showing 00 in the fractional seconds position
4. Turning on the display if it was previously turned off

The display of just two zeros in the fractional seconds positions gives the complete assurance that the stopwatch is "ready to go."

STANDARD MODE

In the STANDARD mode, after a reset has taken place, START/STOP is activated at time t_0. The clock and display are moving simultaneously. A second activation of START/STOP stops the clock and holds the display at time t_{TOTAL}. This completes an event. For timing a second event there are two options. One is to activate START/STOP at the start of the second event. This will momentarily reset the counter and display so that the timing of the second event proceeds from zero. Another activation of START/STOP stops the counter and display at time t_{TOTAL} to end the second event. The other option is to activate RESET after the first event is over. Then the second event proceeds similarly to the first event. As is clear from this description, RESET can be used at any time to reset the stopwatch, including when a timing is in progress. The DISPLAY input can be activated to turn the display off and on. If the display is off when RESET is activated, it will reset and turn on. Turning off the display for timing long events will result in a very substantial power saving.



SEQUENTIAL MODE

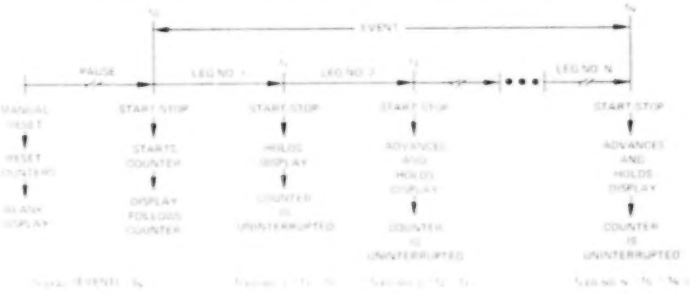
The sequential mode of the stopwatch is designed for timing events consisting of more than one leg (such as relays, multilap races, etc.). After the initial reset the START/STOP is activated at t_0 to start the event. A second activation of START/STOP at time t_1 stops the display to allow t_1 to be read out, while the clock resets and starts counting again instantaneously. At time t_2 an activation of START/STOP enters t_2 (the time of leg no. 2) into the display. This sequence can continue indefinitely. Assuming the total event has N legs, the total elapsed time is then equal to the sum of the N times read out:

$$t_{TOTAL} = t_1 + t_2 \ldots + t_N$$

If it is desired to see the moving clock after a time has been recorded, the DISPLAY switch can be activated to release the display hold and catch up with the moving clock. The display cannot be turned off in the sequential mode. Reset can be activated at any time to reset clock and display.

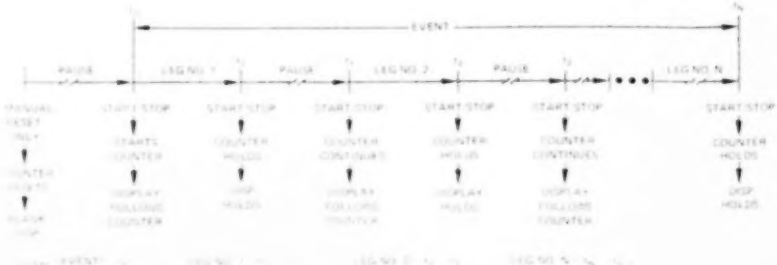
SPLIT MODE

The split mode is another mode for timing multileg events. In contrast to the sequential mode, the timing in the split mode is cumulative. From a reset condition, the START/STOP switch is activated at t_0 to start the counter and display running. A second activation at t_1 stops the display so t_1 can be read out while the counter continues timing. A third activation at t_2 advances the display with the total elapsed time from t_0 to t_2 showing. Finally, at time t_N the total elapsed time of the event is entered in the display. The time of one leg of the event can be obtained by subtraction. The display can be synchronized to the counter (catch-up function) at any time by activating the display switch. To reset the timer, activate reset. The display cannot be turned off in the SPLIT mode.



RALLY MODE

The rally mode is designed for timing of events with interruptions. Consider an N leg event where the legs may be separated by intervals which should not be timed. The rally mode starts with a RESET. At time t_0 the stopwatch is started by activating START/STOP. After this point the RESET function is disabled to prevent accidental resets during long timing intervals. At time t_1 a START/STOP pulse stops counter and display. From here on each leg time is added to the total by a START/STOP pulse at the beginning of the leg and at the end. The individual leg times are determined by subtraction. The display can be turned on and off with the display switch.



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